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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 711

PRESSURE RISE, GAS VIBRATIONS AND COMBUSTION NOISES
DURING THE EXPLOSION OF FUELS

By Professor Wawrziniok

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DURING THE EXPLOSION OF FUELS*

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In the use of piezo-quartz indicators (reference 1) for high-speed automobile engines, the interpretation of pressure-time diagrams made by an oscillograph offers certain difficulties. On the one hand, the scale of the pressure amplitudes is not always the same under all conditions, while, on the other hand, the atmospheric zero line may be shifted from its correct position in the oscillogram. Both depend on the fact that, under certain conditions, either the vacuum in the amplifying tubes or the initial mechanical tension of the quartz body in the indicator housing may change during the running time. Of course this initial pressure may be adjusted to a certain scale at the outset, in which case its magnitude is of secondary importance, but it may change when the heating of the housing increases or decreases the pressure on the quartz body. These changes can be reduced to a minimum, however (e.g., by making the housing of Invar steel), but they still (theoretically) remain. They may therefore cause the above-mentioned displacement of the atmospheric zero line in the oscillogram during the test, the displacement being proportional to the temperature change.

These facts make it necessary to verify the readings of the quartz indicators by direct calibration before and after each series of tests and, on the basis of the results, to determine the scale for the oscillograms. This is somewhat troublesome, but offers no special difficulties with a suitable arrangement of the apparatus.

In the development of the whole method of testing, it was, therefore, not only necessary to insure the reliability of the apparatus, but also to provide for its calibration.

*"Druckanstieg, Gasschwingungen und Verbrennungsgeräusche bei der Verpuffung von Kraftstoffen." Automobiltechnische Zeitschrift, 1933, February 10, pp. 73-78, and March 10, pp. 136-142.

This assumption made it necessary not to conduct the first tests of the new apparatus with engines, where the numerous "variables" make the combustion phenomena more difficult to explore, but with special calorimetric "bombs," in which it is possible to determine accurately the composition of the combustible mixture and to study the course of the combustion unaffected by minor details.*

After overcoming numerous difficulties, an experimental set-up was developed which is shown diagrammatically in figure 1.** The freely suspended test bomb 1, of forged steel, is provided with an electric heating jacket 2. The bomb is closed at the top by a screw cover 4 with a tightening cone 3 through which are led the high-pressure pipes 5 and 6, as also the conduit for the electric igniter z. At the lower end, separated by a strong 0.4 mm (0.016 in.) diaphragm 7, there is a chamber 8 in which the quartz bodies 9 of the indicator are installed and held by the screw 10 with initial pressure. After the manner of Davy's safety lamp, a copper wire gauze was placed over the diaphragm, in order to protect it from the flame and from any change in the initial pressure resulting from an increase in temperature.

For recording the time points according to Schnauffer (reference 2), there are placed inside the bomb the annular electrodes 11 and 12 (J_1 and J_2), made of copper wire. J_1 and J_2 are connected, through packing glands, with the ionization circuits 13 and 14. These are connected with the string galvanometers 15 and 16 whose deflections are reflected by the mirrors 17 and 18 on the film 19 and recorded in the corresponding diagrams. The time diagram is made on the film by an optical time recorder (tuning fork) 20. The passage of a spark in the igniter z of the bomb 1 is effected by the remote ignition contact 21, controlled by the film, through the relay 22 and the induction circuit 23.

*See A.T.Z. (Automobiltechnische Zeitschrift), No. 12 (1932), p. 311.

**The development of the test method and the execution of the tests, as well as the mathematical evaluation of the results, were intrusted to my scientific fellow workers Martin and Schildwachter. The mechanic Liebsch installed the apparatus and assisted in the tests.

For recording the pressure diagram on the film 19, the quartz indicator 9 is connected through the static tube voltmeter 24 with the Braun's tube 25. The beam of light from the Braun's tube is transmitted through a suitable lens 26 to the film.

For recording the noise, there is installed near the bomb a Riegger condenser microphone 27 in a high-frequency circuit which is connected through a low-frequency amplifier with the Braun's tube 28 whose projection device 29 records the sound diagram on the film. (See also A.T.Z., August 20, 1930, p. 546.) Since the sound diagram begins long enough after the recording of the ignition time point, the latter could be added to the sound record. In order to obtain, in the oscillogram for the ignition mark, a single vertical and regulatable deflection, the requisite device was installed as the ignition-point recorder 30 at the output end of the low-frequency circuit of the noise recorder. At the same time it was possible to avoid the coupling of the ignition circuit breaker to the static tube voltmeter of the quartz-indicator circuit by screening and by the introduction of damping resistances ($5 \times 10^4 \Omega$) in the induced ignition circuit.

Figures 2 and 3 show the diagrams for the combustion of hexane vapor of concentration 2.91 percent by volume, corresponding to an air-excess factor of $\lambda = 0.736$, that is, with pronounced air shortage; and 1.82 percent by volume, corresponding to $\lambda = 1.19$, that is, with air excess. The gage pressure in the bomb before the beginning of the combustion was 4 atmospheres.

The pressure curve of the quartz indicator 9 recorded by the beam of light from the Braun's tube 25 together with the tuning-fork diagram represents the time-pressure diagram of the combustion. The pressure scale was determined for four values by two static calibrations by means of compressed air with the aid of precision manometers immediately before and after each combustion test. In every case both calibration curves agreed perfectly, which proved that the heating of the indicator housing by the heat produced by the test did not appreciably affect the initial pressure on the quartz bodies, nor, therefore, the oscillograms.

With a capacity $C = 500 \text{ cm}$ (.16 in.), the time constant T for the static charge at the control grid of the

tube voltmeter was 600 seconds in the most unfavorable case; that is, for $T = CR$ the voltage U at the control grid falls, according to the formula

$$U = U_0 e^{\frac{-T}{CR}}$$

to the 2.718th part of its initial value in 600 seconds. For the mixture $\lambda > 1$, the maximum time between ignition and p_{\max} was about 0.25 second. Due to the time constant, the greatest possible error with respect to the pressure amplitude therefore amounts to only

$$\left(1 - e^{\frac{-0.25}{600}}\right) 100 = 0.04 \text{ percent}$$

The two diagrams above the pressure diagram are records of the two string galvanometers 15 and 16 (fig. 1), which are connected with the ionization electrodes of the bomb. The galvanometer strings are deflected as soon as the flame in the bomb reaches the ionization electrodes J_1 and J_2 . A mean combustion velocity can be calculated from the time and distance. This value holds, however, as will be seen from subsequent explanations, only for the bombs actually used and for the pressure and temperature conditions prevailing at that time.

The continuous pressure rise to the ionization point J_1 admits of the conclusion that, up to this point, there is no disturbance of the advance of the flame front owing to turbulence or reflection from the bomb walls, so that the motion of the flame front can be assumed to be practically linear. The formula used in a previous report (A.T.Z., 1932, p. 237) for this definite process with "linear combustion velocity" therefore seems admissible, all the more since there is hardly any apparent precompression of the still unburned portion of the mixture during the first phase of the combustion.

From the second phase of the combustion, in which the pressure does not increase at a constant rate, but at a diminished rate soon after J_1 , it is obvious that, due to the spreading of the flame toward the walls of the bomb, these walls, despite heating to 150°C . (302°F .), seem to abstract heat from the flame. A "combustion velocity"

v_2 calculated from the flame path J_1 to J_2 would not, therefore, be comparable with the "linear combustion velocity" v_1 , since the former would be affected more than the velocity v_1 by the turbulence of the flame and by the preliminary compression of the still unburned contents of the bomb. The "explosion velocity" of the charge is determined from the length of the bomb and the time (calculated from the instant of ignition) taken to reach the maximum pressure in the bomb. This is an important criterion for the fuel used under the existing test conditions. This explosion velocity is calculated in the same way as the mean flame velocity determined by Nägel (reference 3). It differs from the latter, however, insofar as the cylindrical bomb used does not possess the perfect stereometric regularity of the spherical Nägel bomb with central ignition, for which the propagation of the flame "shell" was optically determined by Lindner (reference 4).

The uppermost curve in the film strips shown in figures 2 and 3 are noise curves. In principle they correspond to the noise curves in my report "Methode zur Messung der Klopfgerausche in Verbrennungskraftmaschinen" (Method for Measuring Detonation Noises in Internal-Combustion Engines). (A.T.Z., 1931, p. 545), with the difference that, in the present case, the pressure and noise curves are recorded simultaneously and synchronously on a common film. Thus it was possible to show, with close approximation, the time of the beginning of the noise and its nature, as likewise its diminution in relation to the pressure development.

The electric current for recording the noise had to be taken from the direct-current system of the institute. Hence the vibrations superposed on this direct current, because of the sensitive high-frequency circuit, set up an interference level, despite the built-in line choke. This level is more or less visible in the noise curves, even before the beginning of the combustion noises. It is relatively low, however, so that it can be readily separated from the frequencies involved.

In agreement with all the recorded noise curves, it is clearly recognizable from figures 2 and 3 that, toward the end of the combustion of the bomb charge, sinusoidal vibrations of low frequency, of about 900 Hertz and small amplitudes, occurred, which, shortly before the maximum of the pressure rise, changed to 1,800 Hertz and then dropped to 1,600 Hertz as the noise died away. With strong concen-

trations of the gas mixture, still higher frequency of about 3,600 Hertz occurred for a short time, in addition to these two frequencies. It appears as if these frequencies were related like harmonics, i.e., in this case, as 1:2:4. These three frequencies are audible as soon as their pressure amplitudes pass the threshold of audibility. They then correspond to the combustion noises heard by other investigators and described as howling, whistling, etc.

Only the predominating fundamental frequency, and of that only the first part of the vibration curve which follows an exponential curve having a duration of about 1/200 second is used for the evaluation. The frequencies calibrated by means of a vibration buzzer (fig. 4), cover a sufficiently broad frequency band for the present tests and serve as the criterion of transmission for the electric sound recorder.

The gradual transition to the fundamental dominating noise frequency of 1,850 Hertz and the attendant gradually increasing amplitude are noticeable in the noise curves. This phenomenon is at first contrary to the noise curves, which correspond to the detonations of engines and in which the transition to the dominating frequency, suddenly becomes visible, with large amplitude (fig. 5). (A.T.Z., 1931, p. 545.) On closer examination, however, it is clear that the first vibration amplitude before the point A is almost of the order of magnitude of the interference level, while the fourth vibration amplitude is already in the maximum. All four vibration amplitudes show a definite percentage increase, a phenomenon similar to the combustion noises in the bomb tests under consideration.

In these tests it could be first demonstrated by the evaluation of a few diagrams (figs. 2, 9, 12, 13, 19) that the amplitude increase (negative decrement) of the combustion noises in the bombs did not occur suddenly, but with an approximately exponential increase. In the present case the decrement for the amplitudes a_1 and a_2 of two successive half-waves is

$$d = \ln \frac{a_1}{a_2}.$$

For the test bombs with all gas mixtures with $\lambda < 1$, the decrement averaged

$$d_{\text{bomb}} \approx \ln (0.8 \text{ to } 0.9).$$

The formula

$$d_{\text{engine}} \approx \ln 0.6,$$

determined with close approximation for the detonation diagram of the Elite engine (fig. 5), supports the assumption that the nonsinusoidal detonation noise in the combustion engine is a phenomenon similar to the combustion noise in the bomb. For comparison, these decrements are represented in figure 6 for both bomb and engine.

Although the time point of the beginning of the noise in the test bomb seems to be shifted toward $-\infty$ through the introduction of the logarithmic relation, the consideration that the ignition takes place in finite time and that the logarithmic function holds only for the process during a limited time, makes the method of interpretation of the vibration diagrams, according to the first visible beginning, appear permissible and correct. (The electric amplification was the same in all these tests, so that the so-called optical threshold can be assumed to be constant.)

While the loudness of the noise depends largely on the nature and concentration of the mixture of fuel vapor and air (percentage composition by volume) and increases with the concentration, the dominating frequency of the noise for all the fuel-air mixtures tested was nearly the same under all conditions. This was about 1,850 Hertz in all tests with the bomb shown in figure 1.

This fact seems to justify the earlier conjecture, based on other experiments, that the combustion noise is somehow connected with the natural vibrations of the bomb caused by impacts, or that the gas vibrations resulting from the combustion are imparted to the walls of the bomb and thus become audible. (Lorentzen, Z. f. angew. Chemie, 1931, No. 7.) This surmise was strengthened by the superposed gas-pressure vibrations, shown by way of example in figure 7, the frequency of which agrees with that of the noise-vibration curve. Both were about 1,850 Hertz, as could be determined from the pressure-time curve by the electric filtering of the gas-pressure vibrations (fig. 9). The voltage had to be increased about a thousandfold.*

*The separation of the frequency, 1,850 Hertz, was done by an alternating-current amplifier, which was connected with the direct-current amplifier. The amplitude of the gas-pressure vibrations amounted to as much as 4 atmospheres according to the tests under consideration.

As proof that, in a bomb mounted on a foundation, the vibrations of the bomb, provided any actually occur, must also be transmitted to the foundation, the vibration curve of the foundation was recorded in conjunction with the noise picture by means of a piezo-quartz concussion recorder (fig. 10). With the natural vibration of the foundation of about 63 Hertz developed by a force liberated in the bomb, the foundation shows upper harmonics of 1,850 Hertz, corresponding to the gas and noise vibrations. These harmonics are doubtless only forced vibrations excited by the bomb itself. The static calibration of the concussion recorder showed that a 12 mm (0.47 in.) oscillograph deflection corresponds to a force $K = 1 \text{ kg}$ (2.2 lb.). Hence, in conformity with the formula

$$K_2 = m a_2 \omega^2 \text{ (fig. 10)}$$

for the position of the concussion recorder, the maximum amplitude could be calculated for $\omega = 2 \pi 1850/\text{second}$ at $a_2 \cong 2.5 \times 10^{-7} \text{ mm}$. This amplitude is of the order of magnitude of interatomic distances. (The mass resting on the quartz bodies amounted to $24/9.81 \text{ kg m}^{-1} \text{ sec}^2$.)

In order to determine whether the natural vibration of the bomb material participates audibly in the combustion noise, further tests had to be made with bombs of other sizes and design. For example, the natural frequency of a thin-walled bomb with a combustion chamber 13.8 cm (5.43 in.) long was determined by striking. It was 5,500 Hertz (fig. 11). The record of the combustion noise was then obtained, as shown in figure 12. An exponentially beginning vibration of 3,300 Hertz is recognized. Aside from the recorded frequency, there are also protracted beats, which are indicative of a second frequency very different from the momentary beat frequency. The 3,300 Hertz frequency can belong only to gas vibrations. Accordingly it is possible that either the gas vibrations are alone audible, insofar as their amplitude falls within the range of the human eardrums, or that, if the gas vibrations have components with a frequency of 5500/second, the natural vibrations of the bomb material induced by them are also audible. In such cases the bomb material may be highly stressed with consequent risk of failure from resonance.

In a third bomb having a combustion chamber 19.7 cm (7.76 in.) long the first frequency of the gas vibration was 2,300 Hertz (fig. 13). The natural vibrations of this bomb were not visible on account of the thickness of its walls. The same was true of the large test bombs.

[The test results permit the supposition that the gas-vibration frequency depends on the shape and length of the combustion chamber. This supposition is supported by the values in table I, which gives the dimensions of the test bombs and the experimentally determined frequencies of the gas vibrations.] From the proportionality of the combustion-chamber lengths and the corresponding gas vibrations we obtain, for the three bombs used, the proportion:

$$25 : 19.7 : 13.8 = \frac{1}{1850} : \frac{1}{2350} : \frac{1}{3360} .$$

(In order to make the proportion exact, the denominators 2300 and 3300 were raised to 2350 and 3360, respectively. These corrections are allowable, since they lie within the region of observed frequency variations.)

From this result it may be concluded that it is simply a question of longitudinal vibrations of the gas column and that the combustion noises are attributable to such vibrations.* (The ignition was effected at the same point in all three bombs, and the concentration of the mixture was the same.)

The drop of 2,300 Hertz in figure 13 is attributable to the effect of the temperature on the velocity of sound, according to formula

$$c = \sqrt{g R T \frac{c_p}{c_o}} \text{ m/s}$$

The noise began with the exponentially rising nonsinusoidal tone of 2,300 Hertz. During the course of about 0.1 second, it fell to 1,700 Hertz. After reaching the frequency of 2,000 Hertz, there appeared for a brief period the previously mentioned double frequency which, in this case, amounted to 4,000 Hertz. The conclusion is thus reached that the superposed higher frequencies are vibrations of the gas column with a shorter wave length, which stands in a definite reciprocal harmonic ratio to the total length of the bomb. For a sound velocity of 900 m/s (2,953 ft./sec.) the fundamental wave length is twice the length of the combustion chamber.

*Lorentsen obtained, for a hexane-air mixture, $p_0 = 6$ atm., $t_0 = 18^\circ \text{C.}$, 4.56 percent by volume with a bomb 25 cm (9.84 in.) long, shortly before the pressure maximum, a vibrating combustion of the frequency $\nu = 1,600$ to 1,700 Hertz.

SPECIAL TESTS

In trying out the above-described new test method, the fuels used in previous investigations, namely, hexane C_6H_{14} and Baku gasoline were employed (A.T.Z., 1932, p. 263). The concentration of the fuel-air mixtures was determined by the Haber-Lowe interferometer and plotted against the excess-air factor according to figure 14.

In the previous investigations the mixtures with excess-air factors of $\lambda = 1.3$ and 1.25 under atmospheric pressure were found to be incapable of explosion. In the above-described tests, on the contrary, under higher initial pressures (4.7 and 10 atmospheres gage pressures) and a higher temperature ($150^\circ C. = 302^\circ F.$), such mixtures were found to be capable of explosion at even higher excess-air factors.

The oscillograms for the various fuel-air mixtures yield the following values:

The combustion time of the bomb charge;

The maximum pressure during combustion;

The relative time point of the beginning of the combustion noise;

The mean linear combustion velocity of the mixture at the beginning of the combustion;

The explosion velocity of the mixture charge with respect to the length of the bomb.

In order to illustrate the dependence of these values on the composition and concentration of the tested fuel-air mixtures, the values are plotted in figures 15 to 18 against the excess-air factor λ for each mixture.

The t curve shows that an optimum of the combustion or explosion time lies at $\lambda = 0.9$, and that accordingly the mixture with the specified excess-air factor $\lambda = 0.9$ has the greatest explosion velocity v_0 . The optimum of the mean linear combustion velocity of the mixture tested cannot be accurately determined from the v_1 curve, due to the scattering of the individual values. It may, however, be assumed, in accordance with the course of the t

and v_0 curves, that it is correct for mixtures with the same excess-air factor $\lambda = 0.9$. The maximum pressure shows no optimum value, since the maximum explosion pressure p_{\max} must naturally rise with increasing concentration of the mixture up to a yet unknown limit.

The explosion noise in the combustion of all the mixtures begins even before the flame front reaches the bottom of the bomb and before the maximum pressure develops. There seems therefore to be some connection here with the detonation in the engine, the cause of which is attributable to the detonation of the mixture remaining toward the end of the combustion. (Schnauffer, V.D.I., April 11, 1931.)

The time intervals between p_{\max} and the visible beginning of the combustion noise were designated by Δt in the present tests and included in the Δt curves. Taking into account the contraction already referred to with respect to the logarithmic insert, the course of the Δt curves shows that the beginning of the noise in mixtures of hexane vapor and air with increasing p_c ($p_c = 4, 7$, and 10 atmosphere gage pressure) at λ_{opt} has a minimum time value which is attributable to the very short combustion time at this point. For the test bomb of 1,350 cm³ (82.4 cu.in.) the shortest time between the beginning of the noise and the maximum pressure was about 0.012 second or, with respect to the total combustion time $t = 0.067$ second, $\Delta t/t = 18$ percent (table II).

Lastly, it is especially worthy of note that, with the same mixture concentrations, the ratio of pressure increase is constant according to the theoretical formula

$$\frac{p_{\max}}{p_c} = \frac{T_{\max}}{T_0} C$$

T_{\max} is the absolute combustion temperature; T_0 , the absolute initial temperature; and the constant C is a factor, which takes into consideration the number of molecules in the reaction.

The pressure-increase ratios p_{\max}/p_c and p_{J_1}/p_c (p_{J_1} = momentary pressure at test point J_1) experimentally determined for hexane, as also the quotients of the instantaneous pressures at the bottom of the bomb and at the

test point J_1 are shown graphically in figure 21. At $\lambda_{opt} = 0.9$ the mean pressure-increase ratio is $p_{max}/p_c =$ about 6.5. The discrepancies in the pressure-increase ratio p_{max}/p_c for $p_c = 4, 7,$ and 10 atmospheres gage pressure are therefore attributable to the variations in p_{max} at strong concentrations. For information concerning the detailed results of the tests, table II gives the individual values corresponding to the mixtures for which $\lambda = 0.7$ to 1.4.

The values for v_1 in the test series for Baku gasoline are not directly comparable with the analogous values for hexane, since, in the tests with the former, the ionization electrode J_1 was placed at a distance of 11.7 cm (4.6 in.) from the ignition point in contrast with the test series with hexane where the distance was only 8 cm (3.15 in.). The consequent discrepancy in the values can, however, be only very small. Since the greater distance of 11.7 centimeters corresponds to a more symmetrical division of the 25 cm (9.84 in.) length of the combustion chamber, only this distance of 11.7 centimeters will be used in future tests. The test series with mixtures of hexane vapor and air at $\lambda = 0.9$ shows no appreciable dependence on the initial pressure p_c with respect to the total combustion time t and the flame velocity v_1 .

The Baku gasoline with $v_0 = 4.12$ m/s (13.52 ft./sec.) at $\lambda = 0.9$ had the greatest explosion velocity of all the mixtures tested. This is considerably lower than the explosion velocities in engines, which, in previous tests ranged up to 16 m/s (52.5 ft./sec.) according to the ignition advance. (For further details see "Mitteilungen des I. f. K., Vol. VI, pp. 7 ff.)

SUMMARY

The results of explosion experiments with mixtures of hexane and Baku-gasoline vapors and air show that the new method is suitable for such tests.

By the simultaneous inertialess recording of the pressure increase, instant of ignition and combustion noises, as well as the path of the flame front, the following facts could be determined.

The maximum pressure during the combustion developed only after the arrival of the flame front at the bottom of the bomb.

The maximum flame velocity during the first phase of the combustion is in the air-deficiency region at $\lambda = 0.9$. This flame velocity and also the combustion period up to the maximum pressure (explosion period) are independent of the initial pressure at $p_c = 4$ to 10 atm. gage pressure.

The combustion noise begins even before the flame reaches the bottom. The time between the visible beginning of the noise in the oscillogram and the maximum pressure is 20 to 30 percent of the total combustion time t .

It is recognized that the noise is a secondary phenomenon of the gas vibrations in the bomb. The maximum amplitude, as experimentally verified, was 4 atmospheres.* The noises consisted throughout of nonsinusoidal tones.

In mixtures with $\lambda < 1$ the noise developed exponentially with close approximation. Since, even in the engine, a similar beginning of the nonsinusoidal detonation noises was found, there seems to be some relationship between the two phenomena.

By tests with three bombs of different combustion-chamber lengths, a direct proportion was established between the length of the combustion chamber and the reciprocal of the Hertz number of the gas vibrations, from which it was concluded that the vibrations of the combustion gases in the bomb were longitudinal. The vibrations had frequencies between 900 and 4,000 Hertz.

For a sound velocity of 900 m/s (2,953 ft./sec.) at $T_{abs} = 2000^\circ \text{C.}$ (3632°F.), the fundamental wave length is twice the length of the combustion chamber.

*As to how far, due to the high frequency of the vibrations, the inertia forces of the indicator affected the records, no conclusion can yet be made.

SUPPLEMENTARY TESTS

In order to discover whether there is any connection between the relations determined in the bomb tests and those existing in engines, several qualitative tests were made with a single-cylinder four-stroke-cycle engine with vertical valves located at the side. The piston was set at the upper dead center, so that the compression space of the engine formed a bomb. This space was filled with a mixture of hexane vapor and air of given concentration, which was ignited by means of the spark plug on the engine, the combustion noise being recorded in the same way as in the bomb tests.

The oscillogram in figure 22 shows that the combustion noise begins and dies away just as in the tests with the small bomb. The noise begins with the frequency of 3,200 Hertz, i.e., with the frequency of the detonation as determined for the engine. The noise then dies away through 2,500 Hertz to 2,100 Hertz. [This agreement indicates that the maximum length of the combustion chamber seems to be the determining factor for the development of the noise.] In the present case this was 13.3 cm (5.24 in.), as measured perpendicular to the cylinder axis which almost exactly agrees therefore with the bomb length of 13.8 cm (5.43 in.). This seems to justify the assumption that the results obtained in the bomb tests correspond in some degree to those obtained in the engine tests and that the detonation noise of the engines is identical with the combustion noises of the bombs. From this it follows that the detonation noises are likewise attributable to longitudinal gas vibrations, which are produced by pressure variations and become audible externally.

This assumption is further supported by the oscillogram in figure 23, where, at 27.9° ignition advance, the noise begins 1/175 second after the ignition and after passing the dead center, but before the production of the maximum pressure in the cylinder, and pressure fluctuations of like frequency are simultaneously visible in the pressure curve. If these were caused by the gas vibrations, their amplitude is not very great. Since, however, the detonation was very loud, these results indicate that the detonation of engines is not so dangerous as has hitherto been assumed.

In the use of knockproof benzol as engine fuel, there was neither any audible noise, nor did the pressure diagram or the noise diagram in the oscillogram (fig. 24) show any indications of gas vibrations during the combustion.

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Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

TABLE I

	Large bomb	Medium bomb	Small bomb
Volume of combustion chamber	1,350 cm ³	~ 485 cm ³	~ 338 cm ³
Diameter of combustion chamber	8.5 cm	5.6 cm	5.6 cm
Length of combustion chamber	25 cm	19.7 cm	13.8 cm
Natural frequency of bomb	-	-	5,500 Hertz
Frequency of gas vibrations	1,850 Hertz	2,300 Hertz	3,300 Hertz

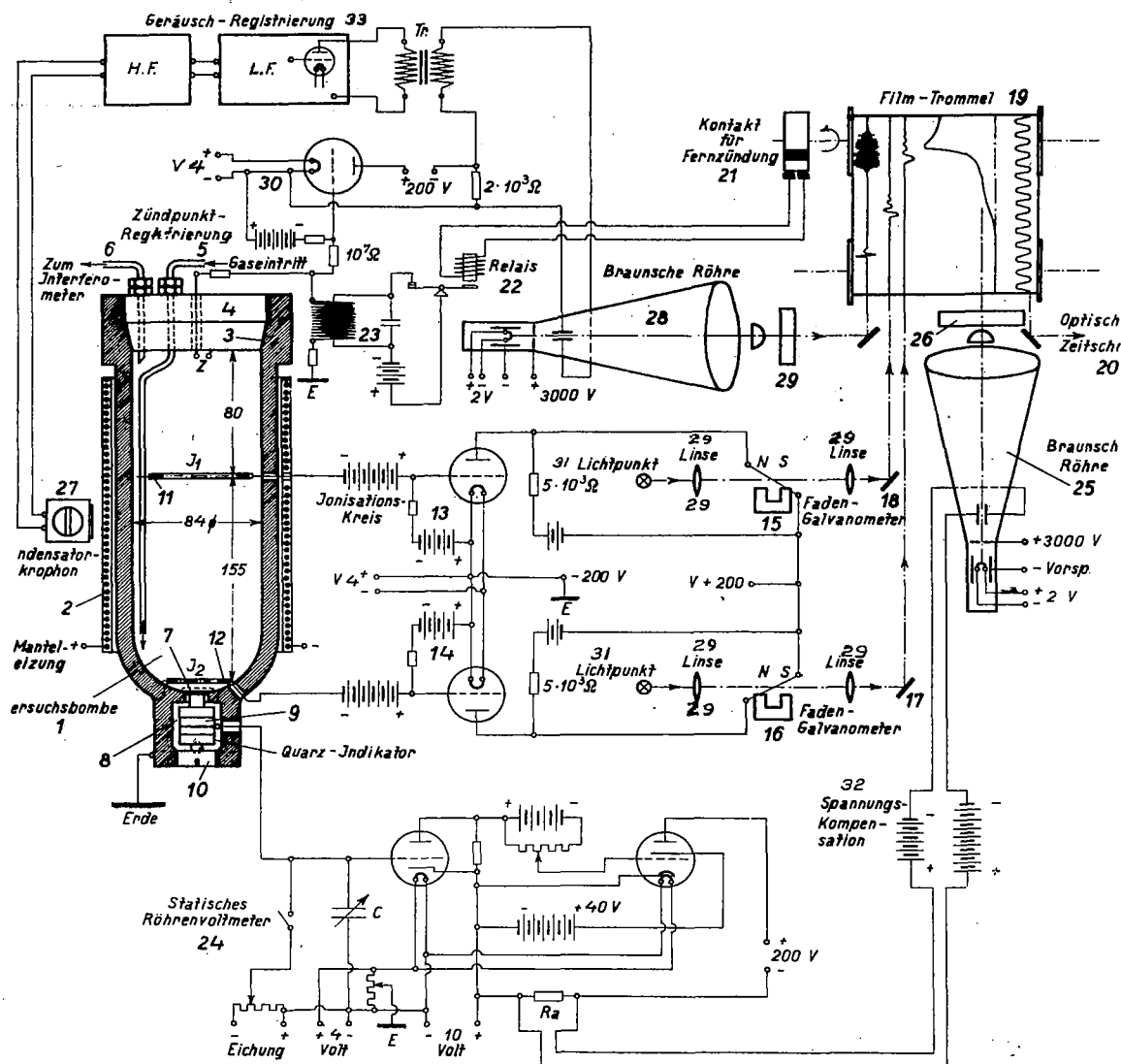
(cm³ × .061023 = cu.in.) (cm × .3937 = in.)

TABLE II

	Concentration of mixture	Initial pressure	Initial temperature	Excess air factor	Combustion time from ignition to maximum pressure for 1350 cm ³ bomb capacity	Linear combustion velocity	Explosion velocity for bomb 23.5 cm long	Maximum pressure	Ratio of pressure increase	Time between visible beginning of noise and maximum pressure	Ratio of Δt to combustion time t
Fuel	Vol. %	P_c	t_0	λ	t	v_l	v_0	p_{max}	$\frac{p_{max}}{P_c}$	Δt	$\frac{\Delta t}{t} 100$
		atm.	C°		second	m/s	m/s	atm.		second	percent
Hexane C ₆ H ₁₄	3.06	4.0	150	0.7	0.094	2.20	2.50	~40.0	~10.00	0.018	19
	2.69			0.8	0.070	3.90	3.36	28.5	7.13	0.018	26
	2.40			0.9	0.067	3.95	3.51	26.0	6.50	0.018	27
	2.17			1.0	0.072	3.60	3.26	24.0	6.00	0.018	25
	1.97			1.1	0.083	3.15	2.83	22.8	5.70	0.018	22
	1.81			1.2	0.097	2.75	2.42	21.8	5.45	0.018	19
	1.67			1.3	0.118	2.30	1.99	20.8	5.20	-	-
	1.55			1.4	0.145	1.85	1.62	20.0	5.00	-	-
"	3.06	7.0	150	0.7	0.086	2.15	2.73	~60.0	~8.57	0.016	19
	2.69			0.8	0.070	3.15	3.36	51.0	7.28	0.013	19
	2.40			0.9	0.067	3.65	3.51	48.3	6.90	0.012	18
	2.17			1.0	0.071	3.55	3.31	46.2	6.59	0.013	18
	1.97			1.1	0.079	3.25	2.97	44.0	6.28	0.015	19
	1.81			1.2	0.095	2.82	2.47	41.5	5.93	0.018	19
	1.67			1.3	0.120	2.30	1.96	39.0	5.57	-	-
	1.55			1.4	0.155	1.70	1.52	36.0	5.14	-	-

TABLE II (Cont'd)

	Concentration of mixture	Initial pressure	Initial temperature	Excess air factor	Combustion time from ignition to maximum pressure for 1350 cm ³ bomb capacity	Linear combustion velocity	Explosion velocity for bomb 23.5 cm long	Maximum pressure	Ratio of pressure increase	Time between visible beginning of noise and maximum pressure	Ratio of Δt to combustion time t
Fuel	Vol. %	P_c	t_0	λ	t	v_l	v_0	P_{max}	$\frac{P_{max}}{P_c}$	Δt	$\frac{\Delta t}{t} 100$
		atm.	C°		second	m/s	m/s	atm.		second	percent
Hexane C ₆ H ₁₄	2.87	10.0	150	0.75	0.087	2.45	2.70	~73.0	~7.30	0.022	25
	2.69			0.8	0.073	3.10	3.22	65.0	6.50	0.017	23
	2.40			0.9	0.062	3.65	3.79	58.0	5.80	0.013	21
	2.17			1.0	0.066	3.65	3.56	56.0	5.60	0.016	24
	1.97			1.1	0.077	3.35	3.05	54.0	5.40	0.023	30
	1.81			1.2	0.096	2.75	2.45	53.0	5.30	-	-
	1.67			1.3	0.126	2.10	1.87	52.0	5.20	-	-
	1.55			1.4	0.180	1.55	1.30	51.5	5.15	-	-
Baku gasoline	2.79	7.0	150	0.7	0.092	2.75	2.55	64.5	9.22	0.014	15
	2.45			0.8	0.063	4.25	3.73	60.0	8.58	0.016	25
	2.18			0.9	0.057	4.50	4.12	55.5	7.93	0.019	33
	1.97			1.0	0.064	4.20	3.67	52.0	7.43	0.023	36
	1.79			1.1	0.074	3.75	3.17	48.0	6.85	0.027	36
	1.65			1.2	0.086	3.30	2.73	44.5	6.35	0.030	35
	1.53			1.3	0.098	2.85	2.40	41.5	5.93	0.034	35
	1.42			1.4	0.112	2.40	2.10	38.5	5.50	0.038	34



- 1, Test bomb. 2, Heating jacket. 3, Tightening cone. 4, Screw cover. 5, Gas inlet. 6, To interferometer. 7, Diaphragm. 8, Quartz chamber. 9, Quartz body. 10, Tension screw. 11, 12, Electrodes. 13, 14, Ionization circuits. 15, 16, Galvanometers. 17, 18, Mirrors. 19, Film reel. 20, Optical time recorder. 21, Contact for remote ignition. 22, Relay. 23, Induction circuit. 24, Static tube voltmeter. 25, Braun's tube. 26, Lens. 27, Condenser microphone. 28, Braun's tube. 29, Lens. 30, Ignition-point recorder. 31, Light point. 32, Voltage compensation. 33, Noise recorder.

Figure 1.-Diagram of apparatus.

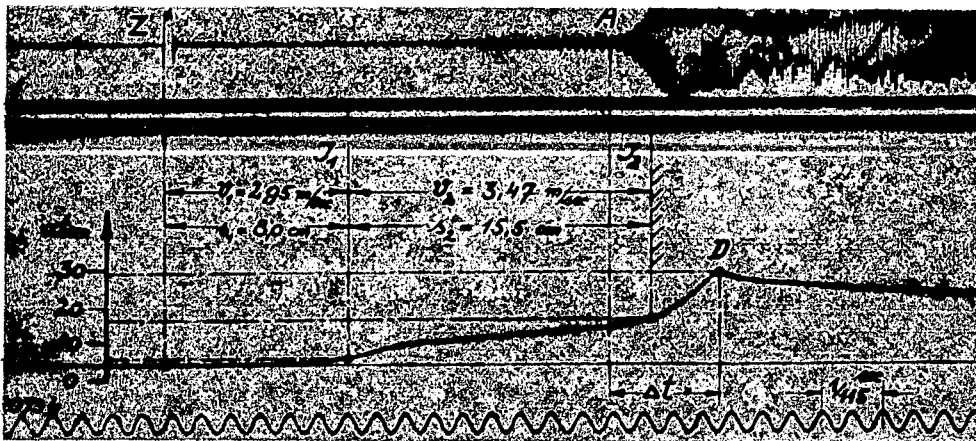


Figure 2.—Combustion of hexane vapor (2.91% by volume). $p_c = 4$ atm.
 $t_o = 150^\circ\text{C}$. $\lambda = 0.736$. Noise frequencies $v_1 \approx 900/\text{sec}$.
 $v_2 \approx 1800/\text{sec}$.

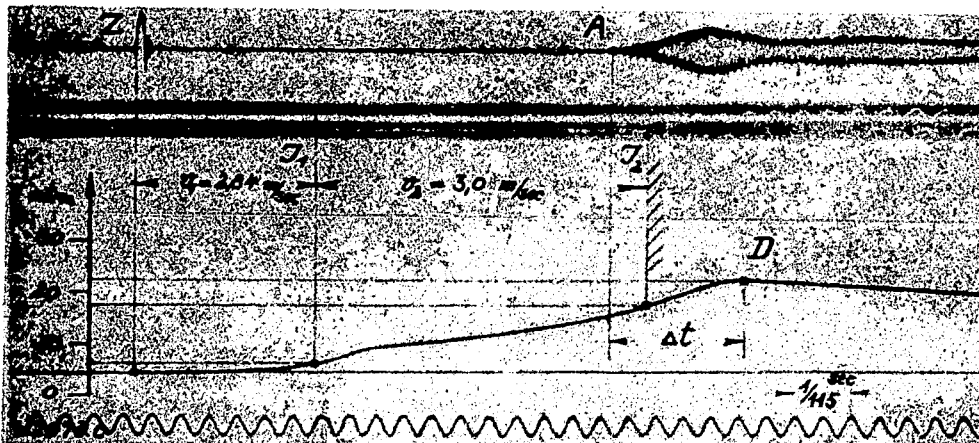


Figure 3.—Combustion of hexane vapor (1.82% by volume). $p_c = 4$ atm.
 $t_o = 150^\circ\text{C}$. $\lambda = 1.19$. Noise frequency $v \approx 1900/\text{sec}$.

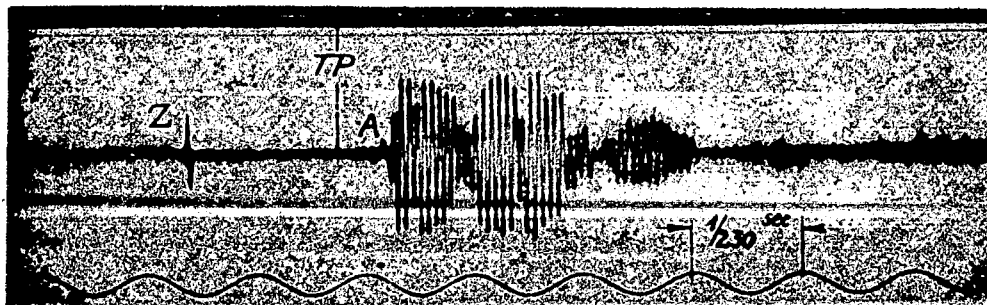


Figure 5.—Detonation noise of an Elite engine. $n = 1000/\text{min}$. Ignition advance 40° . Noise frequency $v \approx 3340/\text{sec}$.

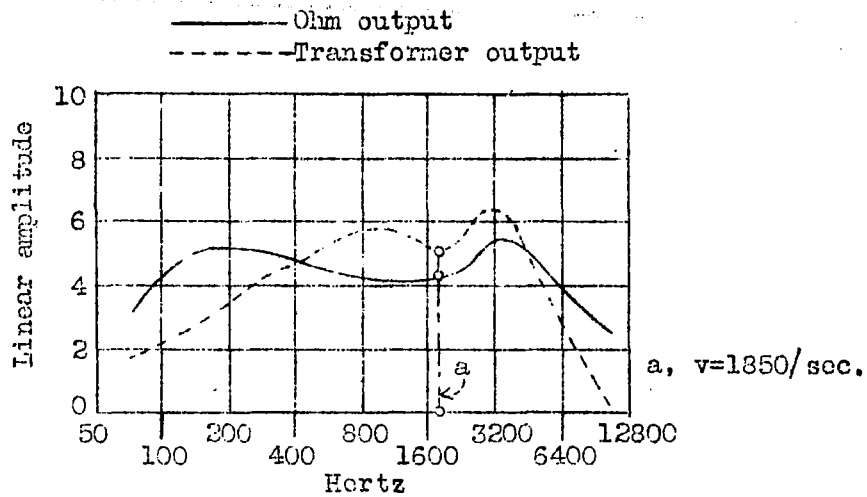


Figure 4.-Frequency curves of the electro-acoustic transmission.

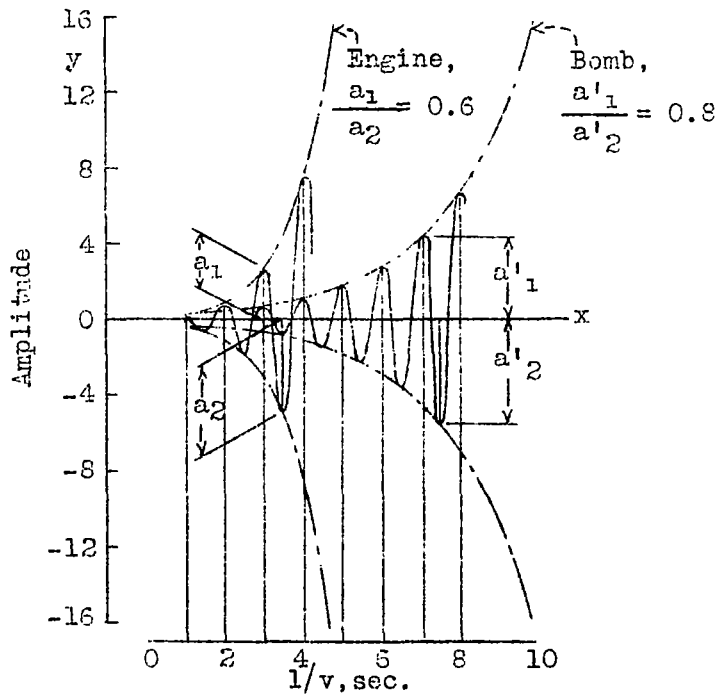


Figure 6.-Amplitude increase of combustion noise in engine and in bomb.

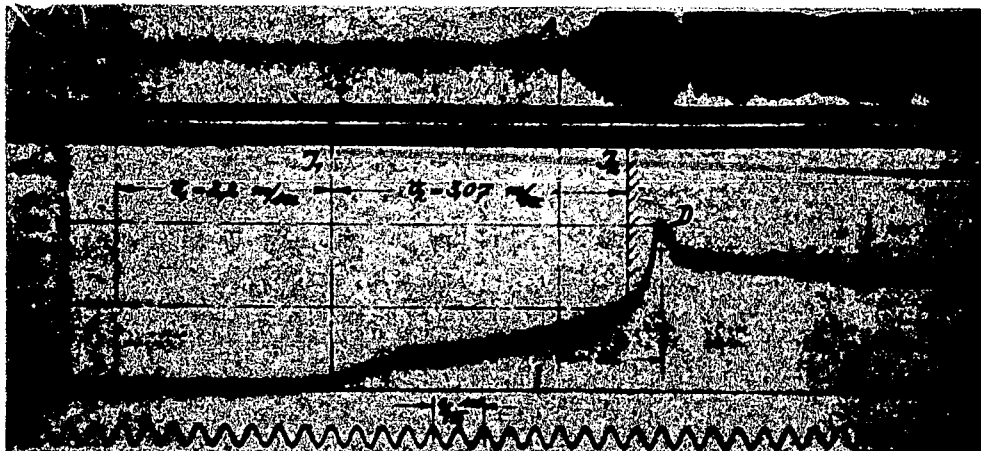


Figure 7.--Combustion of hexane vapor (2.92% by volume). $p_c = 10$ atm.
 $t_0 = 150^\circ\text{C}$. $\lambda = 0.735$. Noise frequency $\nu \approx 1850/\text{sec}$.

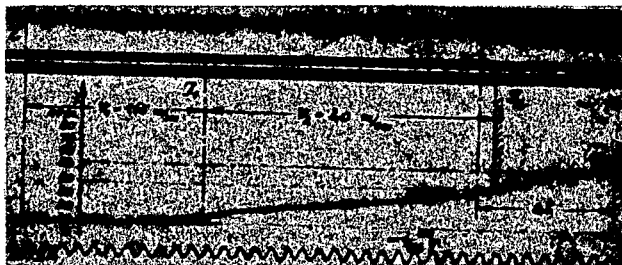


Figure 8.--Combustion of hexane vapor (1.54% by volume.) $p_c = 10$ atm.
 $t_0 = 150^\circ\text{C}$. $\lambda = 1.41$. Noise frequency $\nu \approx 1850/\text{sec}$.

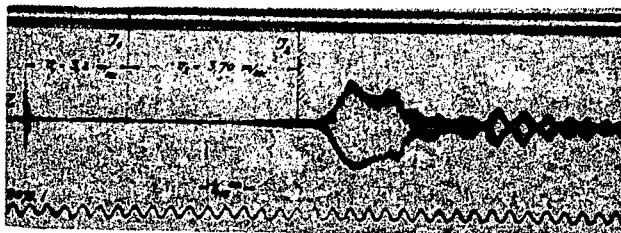


Figure 9.--Electrically separated gas-pressure vibrations. Hexane vapor. $p_c = 10$ atm. $t_0 = 150^\circ\text{C}$. $\nu \approx 1850/\text{sec}$.

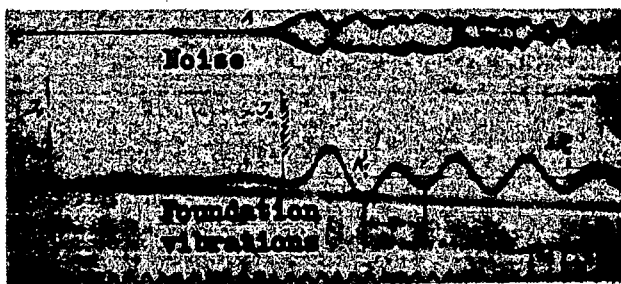


Figure 10.--Foundation vibrations for the combustion of hexane vapor in the firmly secured bomb. Noise frequency $\nu_2 \approx 1800/\text{sec}$.
Amplitude $a_2 \approx 2.5 \times 10^{-7}\text{mm}$.

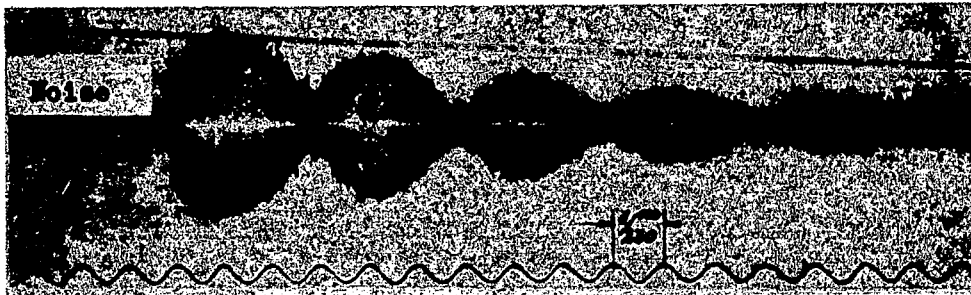


Figure 11.-Noise diagram of a mechanically struck, thin-walled bomb with combustion chamber 13.8 cm long. Natural -vibration frequency $\nu \cong 5500/\text{sec.}$

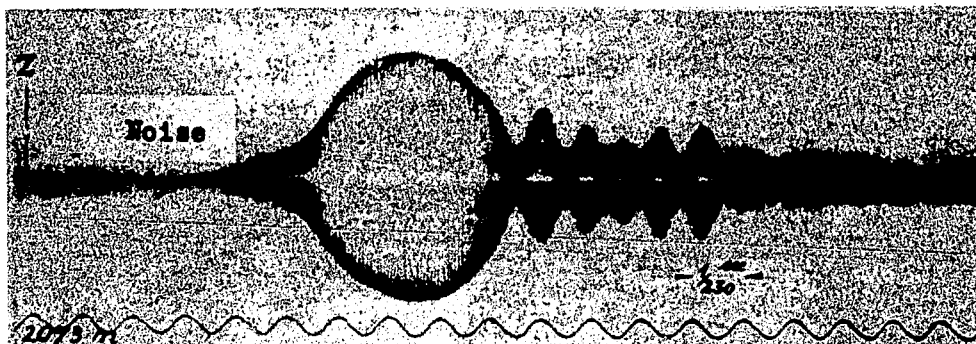


Figure 12.-Combustion noise in thin-walled bomb with combustion chamber 13.8 cm long. Noise frequencies $\cong 3300/\text{sec.}$



Figure 13.-Combustion noise in bomb with combustion chamber 19.7 cm long. Noise frequencies: $\nu_1 = 2300/\text{sec.}$; $\nu_2 = 4000/\text{sec.}$

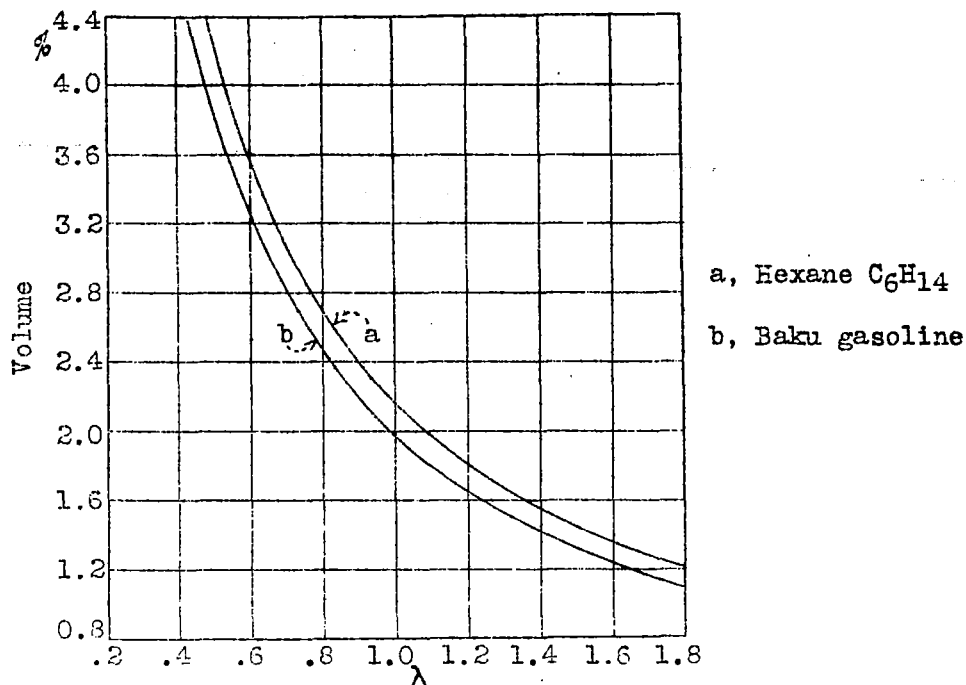
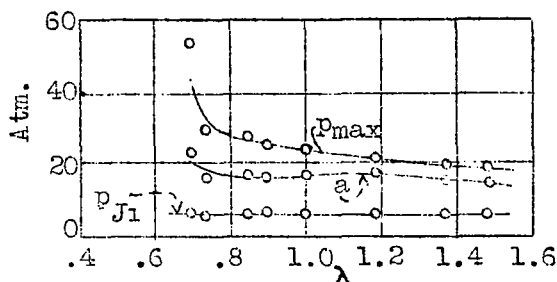
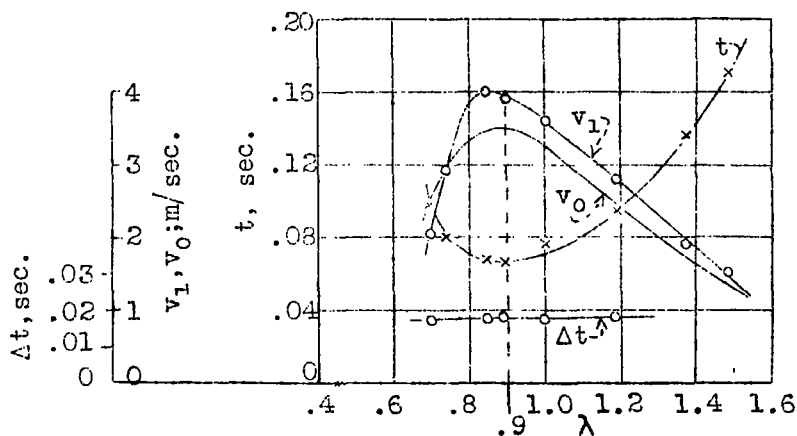


Figure 14.-Concentrations of the fuel-air mixtures used in the tests.



a, p_{bottom}

Figure 15.-Combustion times, pressures and velocities for mixtures of hexane vapor and air at 4 atm. plotted against the excess-air factor λ .

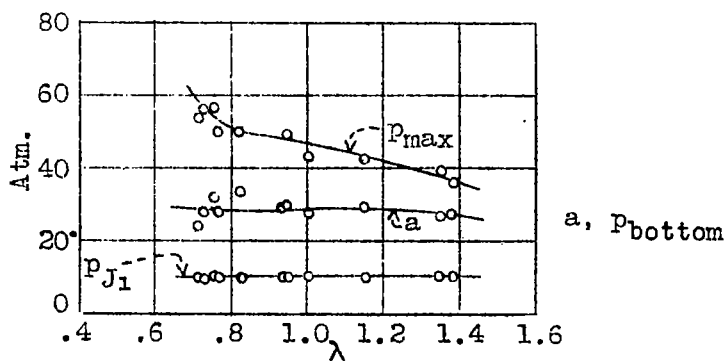
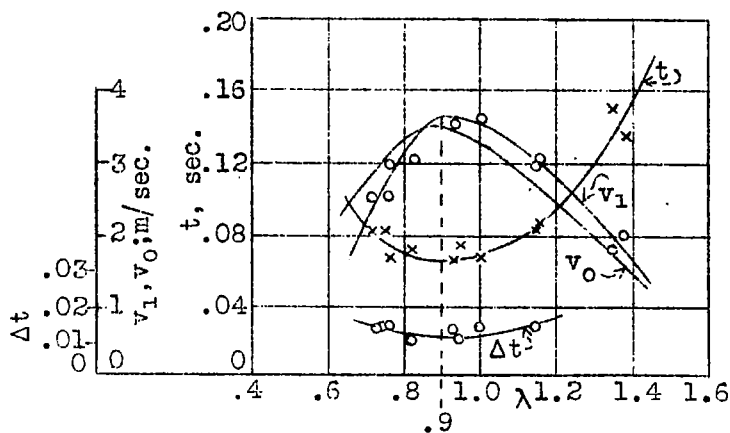


Figure 16.-Combustion times, pressures and velocities for mixtures of hexane vapor and air at 7 atm. plotted against the excess-air factor λ .

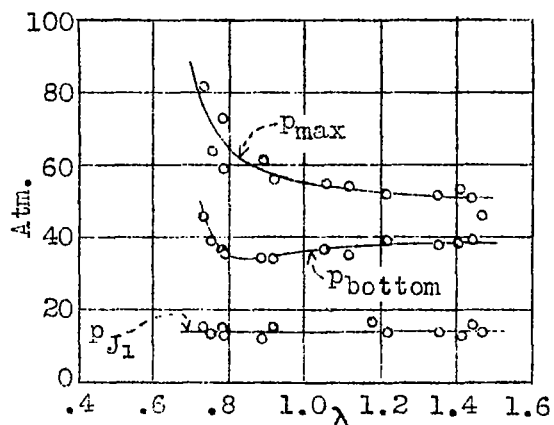
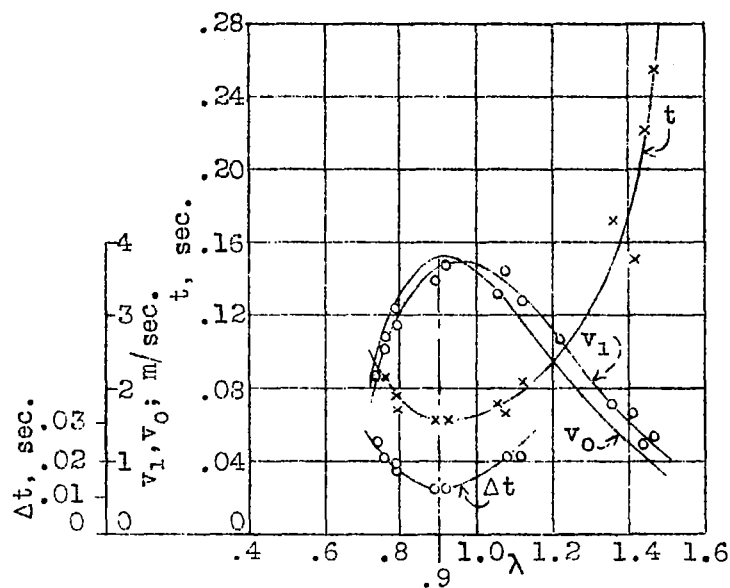


Figure 17.-Combustion times, pressures and velocities for mixtures of hexane vapor and air at 10 atm. plotted against the excess-air factor λ .

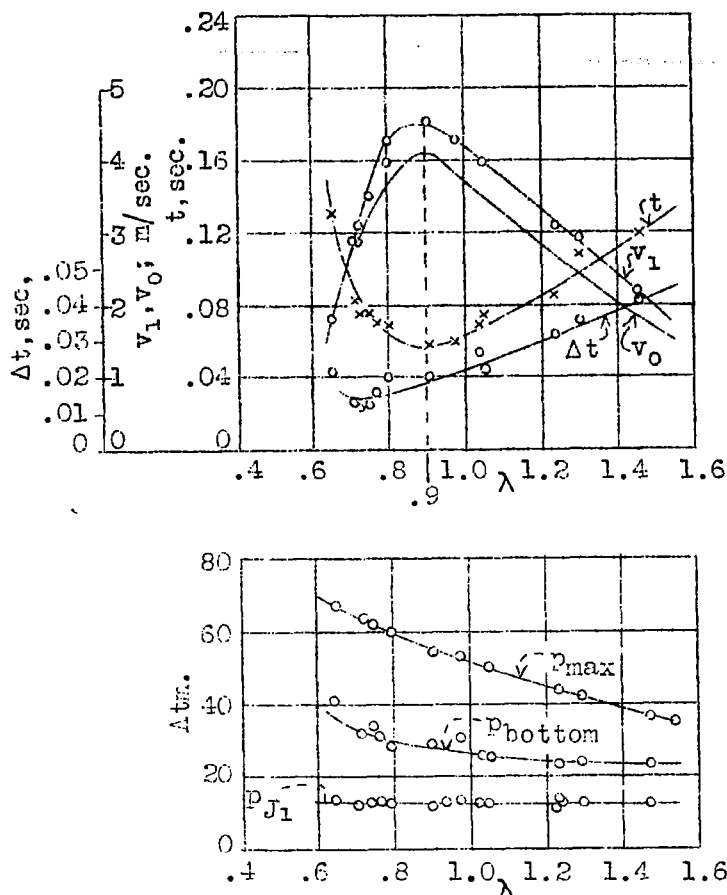


Figure 18.-Combustion times, pressures and velocities for mixtures of Baku gasoline and air at 7 atm. plotted against the excess-air factor λ .

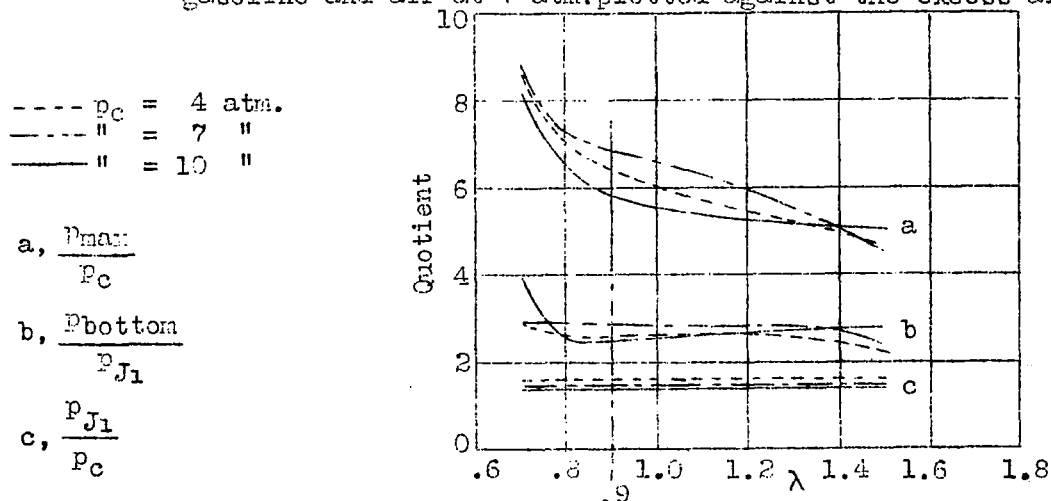


Figure 21.-Quotient of the instantaneous pressures in the explosion of mixtures of hexane vapor and air plotted against the excess-air factor λ .

Figure 19.
Combustion of Baku gasoline vapor (2.62% by volume). $p_c = 7$ atm. $t_0 = 150^\circ\text{C}$. $\lambda = 0.747$. Noise frequency $\nu = 1800/\text{sec}$.

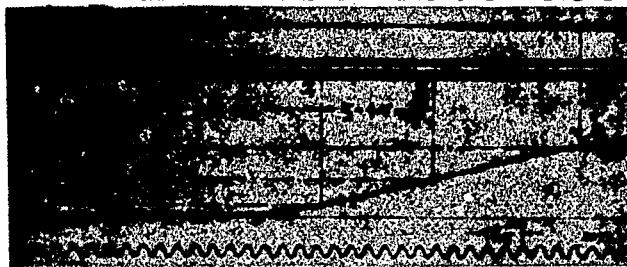
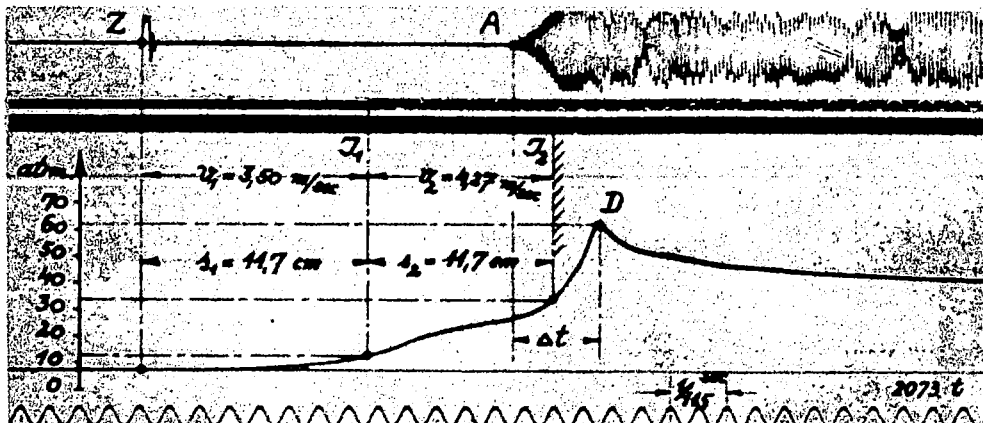


Figure 20.—Combustion of Baku gasoline vapor (1.36% by volume). $p_c = 7$ atm. $t_0 = 150^\circ\text{C}$. $\lambda = 1.457$. Noise frequency $\nu = 1800/\text{sec}$.

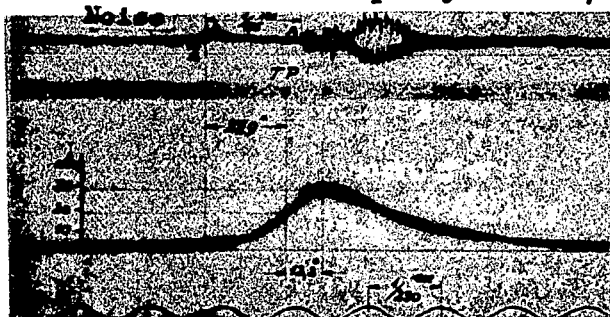


Figure 23.—Pressure-time diagram of running engine. $n = 1000/\text{min}$. Gasoline. Detonation frequency $\nu = 3200/\text{sec}$. Film velocity 7 m/s .



Figure 24.—Pressure-time diagram of running engine. $n = 1000/\text{min}$. Benzol. Film velocity 7 m/sec .

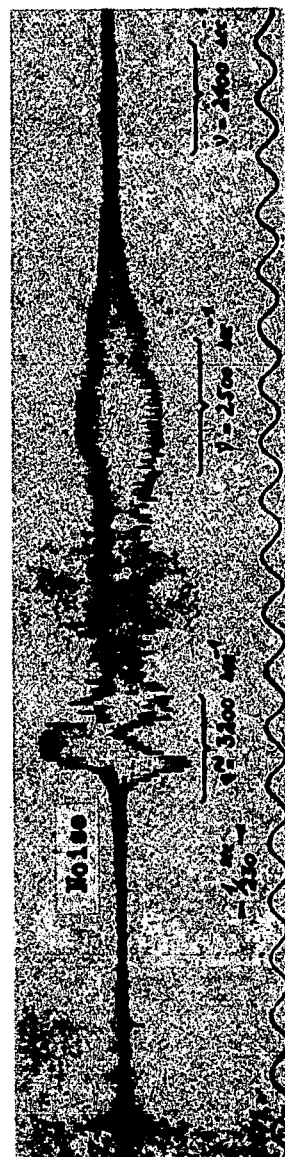


Figure 22.—Engine cylinder operating as a bomb through the arrest of the piston at the top dead center.

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